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Generation of more than 300 mW diffraction-limited light at 405 nm by second-harmonic generation of a tapered diode laser with external cavity feedback

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ABSTRACT

We have constructed a blue laser source consisting of a single-frequency tapered diode laser with external cavity feedback that is frequency doubled by a quasi-phase matched KTP (PPKTP) in a bowtie ring cavity and extract more than 360 mW of power at 405 nm. The conversion efficiency from fundamental laser power to second harmonic power is 35 %, while it is 64 % from coupled fundamental power to extracted blue light. Thermal effects and gray tracking set an upper limit on the amount of generated blue light.

Keywords: Second harmonic generation, external cavity diode lasers, PPKTP, external cavity second harmonic generation, tapered diode laser.

1. INTRODUCTION

Continuous-wave (CW) light in the blue spectral region around 400 nm is of interest for many applications within research, medicine and industry. Gas lasers are available at certain distinct wavelengths in the blue spectrum but with limited power and tunability. Blue lasers at 405 nm based on GaN diodes are currently limited to output powers below 100 mW with single spatial mode output and even lower in single longitudinal mode operation. A commonly used approach in reaching the blue part of the spectrum is second harmonic generation of near-infrared solid-state lasers or diode lasers. The second harmonic generation can be performed internal to the laser resonator^{1,2} or in external enhancement resonators^{3,4}. Using common diode-pumped solid-state lasers it is only possible to reach blue wavelengths above 440 nm⁵ although the use of Ti:Sapphire lasers extend the spectral coverage of solid-state lasers to shorter wavelengths. The Ti:Sapphire laser, however, has only limited efficiency and needs a high power pump source for the generation of high power tunable light. An interesting alternative to the Ti:Sapphire laser is the use of diode lasers for the second harmonic generation. Tunable single-mode diode lasers are limited to output powers of a few hundred milliwatts. The use of tapered laser structures has recently increased the single-mode output from diode lasers into the Watt-level⁶. Employing external cavity feedback to tapered amplifiers has been shown to force the laser into single longitudinal mode operation with output powers approaching 2 W⁷; in this case virtually all free-running power is contained in the single-frequency output. Furthermore, the external cavity feedback enables tuning of the wavelength across the entire gain profile of the tapered amplifier with a typical tuning range of 30-50 nm^{7,8}. Second harmonic generation of an external cavity tapered laser at 780 nm has been demonstrated with a second harmonic output power of 233 mW at 390 nm⁹. Here we report on the generation of up to 364 mW blue light at a wavelength of 405 nm. This is achieved by frequency doubling of an external cavity tapered diode laser in an external enhancement cavity containing a periodically poled KTP crystal. Generation of higher output powers is prevented by thermal effects due to absorption and gray tracking in the non-linear crystal.

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2. TAPERED AMPLIFIER STRUCTURE

A tapered amplifier diode structure was designed for operation in an external cavity setup. Especially the vertical divergence was kept small to ensure efficient coupling to the external cavity. To avoid damage by the back-coupled light the near field width has to be large enough and well confined to the waveguide.

The laser structure consists of GaAsP tensile strained single quantum well (SQW) embedded in a 3 μm thick $\text{Al}_{0.45}\text{Ga}_{0.55}\text{As}$ waveguide. The amplifier is based on a super-large optical cavity structure¹⁰ with a vertical divergence angle as low as 15° (FWHM).

The tapered amplifier consists of an index guided ridge-waveguide (RW) section and a gain guided tapered section. The length of the RW section is 1 mm and the taper length is 3 mm. The width of the ridge section is 3 μm . The taper angle is 4°.

For use with external cavity feedback the RW back facet was coated to a reflectivity below 0.1% while the taper output facet reflectivity was chosen to 0.5%. The taper output facet reflectivity is chosen higher than for laser devices due to low values of the external cavity feedback compared to laser devices. A lower reflectivity causes the laser threshold to increase rapidly.

3. EXTERNAL CAVITY TAPERED LASER

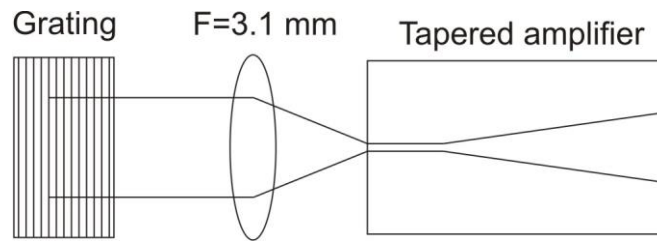


Fig. 1. Experimental setup of the external cavity tapered laser using a diffraction grating external cavity.

The setup for the external cavity tapered laser is shown in figure 1. The laser is operated in the Littrow configuration¹¹ with the first order diffracted beam from the grating directed back into the amplifier. The external cavity consists of an aspheric lens with a focal length of 3.1 mm and a numerical aperture of 0.68. The diffraction grating is a gold coated ruled grating with 1200 grooves/mm and a blaze wavelength of 750 nm and it is oriented with the grooves parallel to the active region of the amplifier. The laser is linearly polarized along the fast axis and thus the maximum diffraction efficiency of the grating is used^{11,12}. The length of the external cavity is approximately 15 mm. The resulting laser cavity is formed between the diffraction grating and the output facet of the tapered amplifier. The components of the external cavity laser are all mounted on a temperature controlled base plate to increase the stability of the laser. The temperature of the base plate is kept at 25°C throughout the experiments.

The output from the laser is collimated in the fast axis using an aspheric lens with 3.1 mm focal length and a numerical aperture of 0.68. The resulting divergence and astigmatism in the slow axis is corrected using a cylindrical lens with a focal length of 50 mm. All lenses are antireflection coated for near-infrared wavelengths in order to minimize coupled cavity effects and losses.

Rotation of the grating provides tuning of the laser wavelength. The output power at different wavelengths is shown in figure 2 (A) with the amplifier current fixed at 3 A. The tuning range (FWHM) is approximately 26 nm and 1.41 W of output power is achieved at a wavelength of 812 nm. More than 1 W of output power is obtained in the range 802-820 nm. The laser is operating in a single longitudinal mode as shown in figure 2 (B). The spectrum is measured with an optical spectrum analyzer (Advantest Corp. 8347) and shows a line width of below 0.004 nm limited by the resolution of the optical spectrum analyzer. The side mode suppression reaches approximately 20 dB and the amplified spontaneous emission is suppressed by more than 40 dB. Using a home made scanning Fabry-Perot interferometer the short term line width has been measured to be less than 1 MHz.

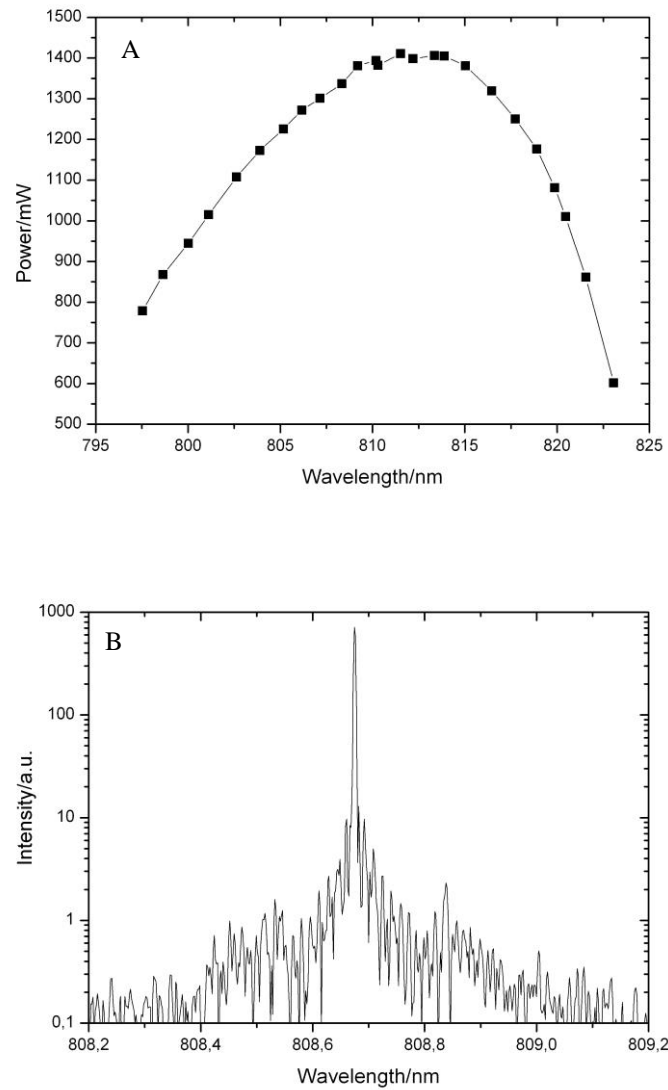


Fig. 2. (A) Tuning range of the external cavity tapered laser at a fixed current of 3 A and a temperature of 25°C. (B) Laser spectrum obtained from an optical spectrum analyzer at a current of 3 A.

The light-current characteristic of the laser has been measured and is displayed in figure 3 at a wavelength of 812 nm. The laser threshold is at a current of approximately 1.8 A. The slope efficiency of the laser is approximately 1.13 W/A. The beam quality parameter M^2 of the laser has been measured to be less than 1.2 for both axes at an output power of 1.4 W.

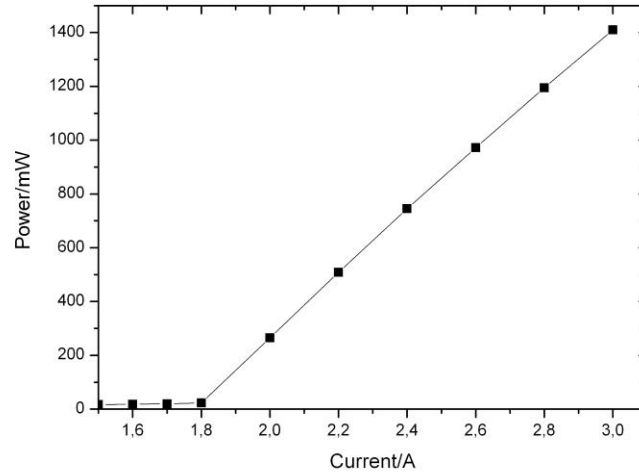


Fig. 3. Light current characteristic for the external cavity tapered laser at a wavelength of 812 nm.

4. SECOND HARMONIC GENERATION

The external cavity tapered laser was used as a pump source for second harmonic generation. In order to achieve efficient conversion the SHG process was performed in an external enhancement cavity. The cavity setup is a four-mirror bowtie configuration. The experimental setup is shown in figure 4. The collimated laser output is sent through an optical isolator to avoid feedback to the laser and the laser beam is mode matched to the SHG cavity using cylindrical lenses. The external cavity consists of two plane mirrors (M1 and M2) and two mirrors with a radius of curvature of 51.8 mm (M3 and M4). The input coupling mirror M1 is coated for a reflectivity of 95% at 810 nm while the remaining mirrors are coated for high reflectivity at 810 nm. All mirrors have been coated for high transmission at 405 nm. The plane highly reflecting mirror, M2, is mounted on a translating piezo in order to control the cavity length and keep the cavity on resonance with the laser frequency. The material employed for the second harmonic generation is a 10 mm long PPKTP crystal poled with a grating period of $\Gamma = 3.4 \mu\text{m}$ and an aperture of 1 mm x 2 mm. The crystal is anti-reflection coated at both the fundamental and second harmonic wavelengths and placed in an oven between the two curved mirrors. The distance between the two curved mirrors is 66 mm and the remaining distance is approximately 146 mm. This generates a beam waist radius of approximately $130 \mu\text{m}$ between the plane mirrors and $42 \mu\text{m}$ in the PPKTP crystal. In order to minimize thermal effects due to absorption in the PPKTP crystal the beam waist radius in the PPKTP crystal is far from the optimum of approximately $16 \mu\text{m}$ ¹³. The thermal effects have previously been shown to limit the amount of power obtainable from an external cavity PPKTP frequency doubler^{14,15}. The large beam waist lowers the conversion efficiency of the PPKTP crystal slightly but greatly enhances the stability of the cavity.

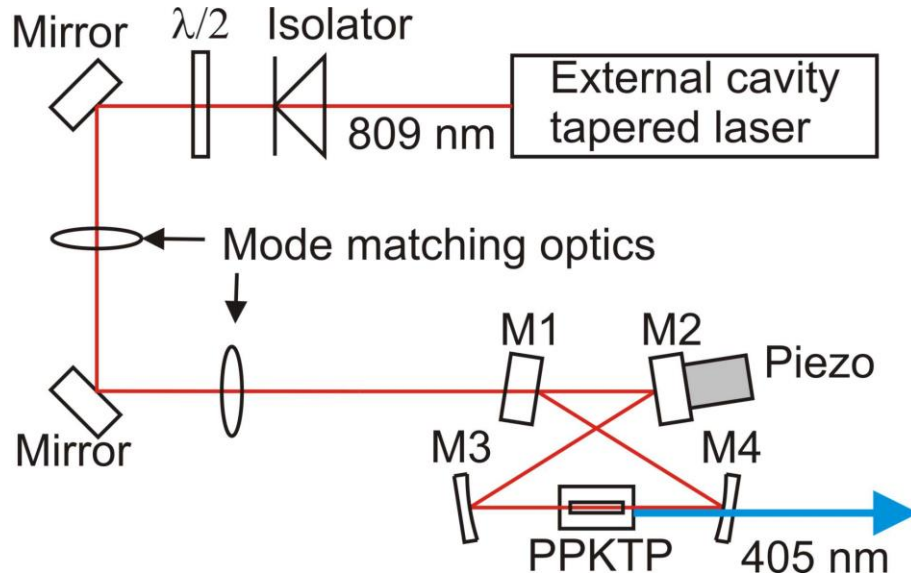


Fig. 4. Experimental setup for the external cavity SHG. M1 is the input coupling mirror with 95 % reflectivity at 810 nm and M2, M3 and M4 are all highly reflecting at 810 nm. The leaking 809 nm light in the output beam is filtered using a short-pass filter.

The extracted blue power is plotted against the mode matched pump power in figure 5. The maximum obtained blue power is 364 mW at a coupled fundamental power of 570 mW corresponding to a conversion efficiency of 64 %. The conversion efficiency is as high as 67 % at a coupled fundamental power of 450 mW but drops slightly at the highest coupled power level. Theoretically expected values are included in figure 5 for comparison¹⁶. In the theoretical curve the measured passive losses of 2.0 % and the single-pass conversion efficiency $\Gamma_{\text{eff}} = 0.83 \text{ \%}/\text{W}$ has been used⁷.

The extracted blue power follows the theoretically expected with high accuracy for coupled pump powers below 300 mW. For higher power levels the extracted blue power becomes smaller than the theoretically expected due to thermal effects in the nonlinear crystal. The thermal effects are caused by absorption of both fundamental and second harmonic light and will be discussed below. The measured blue power has not been corrected for losses in the blue beam passing the output coupler and the short-pass filter.

The wavelength of the external cavity laser is tunable over a large wavelength range. By changing the temperature of the PPKTP crystal it is possible to achieve phase matching for different fundamental wavelengths. A temperature change of approximately 35°C changes the phase matched fundamental wavelength by 2 nm and thereby the second harmonic wavelength is changed by 1 nm.

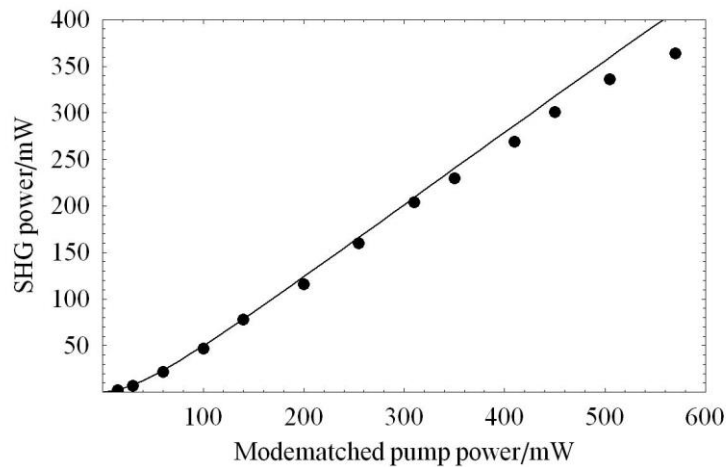


Fig. 5. Measured SHG power versus mode matched power into the cavity. The solid line is calculated using $\eta = 0.83\%/W$ and 2% passive losses.

The PPKTP is absorbing both the fundamental and the second harmonic beam. The absorption coefficient at the fundamental wavelength is relatively modest but increases significantly at shorter wavelengths¹⁷. The absorption coefficient in KTP at 473 nm was measured to be in the range $0.034 - 0.085 \text{ cm}^{-1}$. At 405 nm the absorption increases and reaches values in the range $0.12 - 0.2 \text{ cm}^{-1}$ for the three samples used in the measurement. At 423 nm the absorption coefficient of a PPKTP sample was measured to 0.151 cm^{-1} and at 846 nm a value of 0.018 cm^{-1} was measured¹⁴. The absorption gives rise to heating of the crystal. The presence of the fundamental beam alone provides some thermal effects as the intensity of the fundamental beam is enhanced in the cavity. The presence of the second harmonic beam, however, rapidly increases the heating of the crystal due to the much higher absorption coefficient of the blue light. The heating of the PPKTP crystal is affecting the uniformity of the resonance peaks of the cavity¹⁸. When the cavity is tuned into resonance by shortening the cavity the amount of absorbed power is increased and the heating of the crystal causes the effective optical path length to increase. This increase in optical path length is causing the cavity resonance to effectively shift to a shorter cavity length and the circulating power will slowly increase until the resonance peak is reached. Hereafter the temperature of the crystal decreases and the cavity is quickly forced out of resonance. The result is a broadening of the resonance peak. When the cavity length is increased the heating of the crystal has the opposite effect and quickly forces the cavity out of resonance resulting in a sharp cavity fringe. A more detailed investigation of this problem has been performed elsewhere^{15,18}. An experimental example of this is given in figure 6, where the beam waist radius in the PPKTP crystal has been lowered to approximately $25 \text{ }\mu\text{m}$ and the coupled fundamental power is approximately 400 mW. The scanning speed is 20 Hz and over approximately 1.5 FSR. As evident from figure 6 the difference between the contracting and expanding cavity resonance peaks is very large and it is very difficult to lock the cavity based on this transmission peak.

Increasing the beam waist radius to $42 \text{ }\mu\text{m}$ lowers the thermal load in the crystal and the resonance peaks are becoming closer to the expected shape. Figure 7 gives examples of cavity resonance peaks with the PPKTP crystal off phase matching ((A) no blue light) and phase matched ((B) 300 mW blue light). It is obvious that the resonance peaks are more similar in shape and locking to these resonance peaks is possible. It is also evident from figure 7 that the presence of the blue light increases the thermal effects in the crystal as expected.

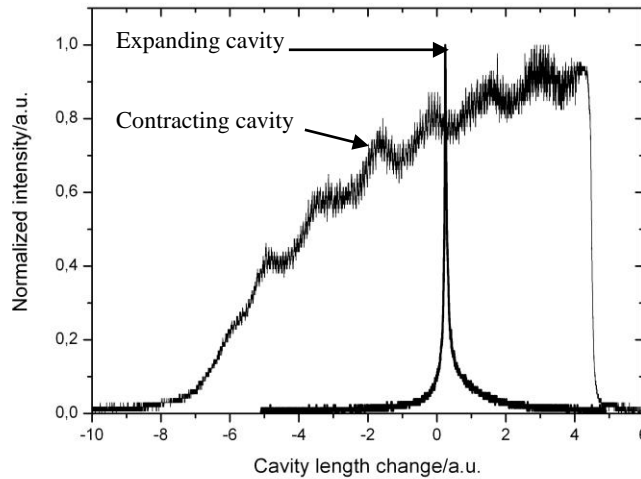


Fig. 6. Resonance peaks obtained for the scanned cavity with a beam waist radius of approximately $25 \text{ }\mu\text{m}$. The difference in width between the cavity resonance peaks of the contracting (thin line) and expanding (bold line) cavity is more than a factor of 100.

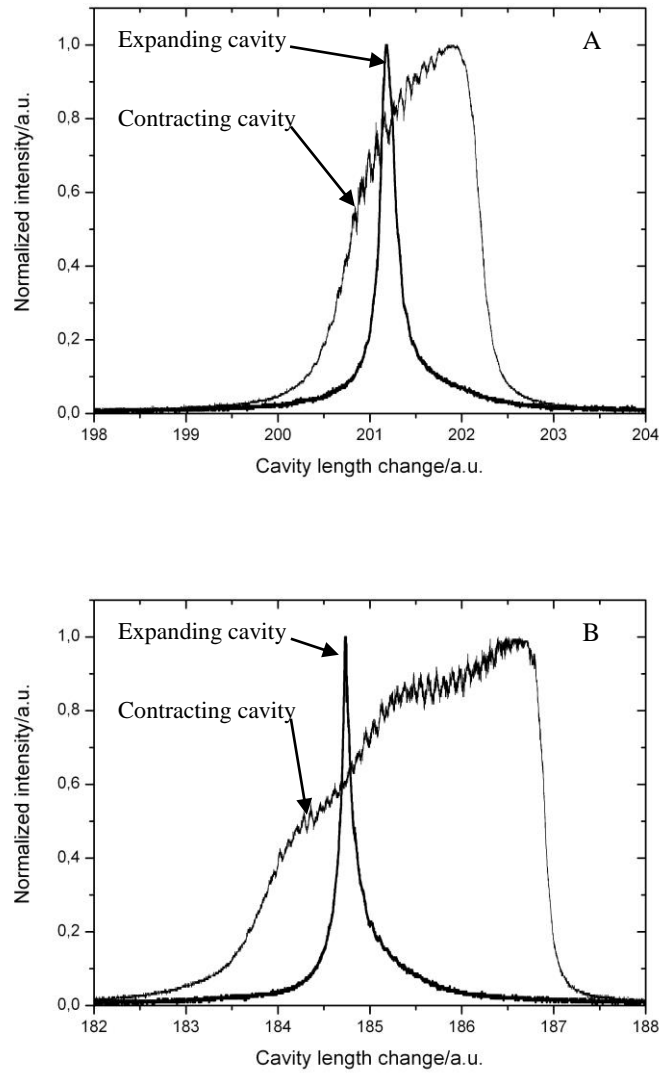


Fig. 7. Resonance peaks obtained for the scanned cavity with a beam waist radius of approximately $42\text{ }\mu\text{m}$ without blue light (A) and with blue light (B). In (A) the difference in width between the cavity resonance peaks of the contracting (thin line) and expanding (bold line) cavity is a factor of 7 and in (B) the difference is a factor of 18.

It has been observed that the blue output power degrades over time on a time scale of minutes. By moving the crystal perpendicular to the optical axis it is possible to regain the high output power. This indicates damage to the crystal and a visual inspection under a microscope reveals darkened regions in the crystal, especially near the output facet of the crystal. These darkened regions are due to gray tracking in the crystal. Gray tracking has previously been reported for generation of green light by single-pass second harmonic generation of high peak power lasers^{19,20} but also with use of continuous wave green lasers²¹.

5. CONCLUSION

We have generated more than 360 mW of blue light at a wavelength of 405 nm with a conversion efficiency of 64 % from mode matched fundamental power to extracted blue power. An external cavity tapered laser at 809 nm is used as a pump source and is capable of delivering more than 1.35 W of power in a nearly diffraction-limited beam with M^2 less than 1.2. The laser is coupled to an external enhancement cavity consisting of four mirrors and a PPKTP crystal. In order to be able to lock the cavity to the laser frequency it proved necessary to increase the beam waist to more than 2.5 times the theoretical optimum due to thermal effects in the PPKTP crystal.

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